Force Between Current-Carrying Wires

Introduction: Magnetic levitation (or maglev) has become familiar terminology. It refers to objects that rise or float when magnetic forces are involved. One application, of course, is Maglev trains. In today's lab, we will observe a form of magnetic levitation. What we will do is send charges in opposite directions through parallel wires, one of which is fixed in position. The other wire will rise as the current increases. (We will also measure the force on the wire.) There is a related phenomenon that we are all familiar with. Specifically, we have all seen magnets exert a push or a pull on objects made of iron such as a paper clip. There is a strange, but true fact concerning all of these situations:

LEVITATING!

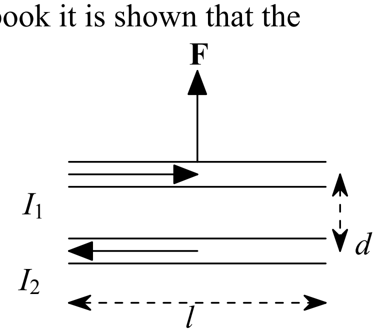
The long-awaited maglev vehicle is hoisted onto the guideway Thursday morning at Old Dominion University after traveling two days from its test site in Florida. Following adjustments, reattachments and the placing of additional track, test runs should begin in mid-July. The grand opening is scheduled for late September.

The force that actually lifts a train or wire or pulls a paper clip to a magnet is not a magnetic force.

The reason is simple. The magnetic force acts only on the moving charges (usually a few of the electrons) and not on the bulk of the material. It is those few, moving charges that push or pull on the bulk of the material via the electrical force.

Also, the statement that a magnetic force "lifts" or "pulls" can create the misconception that a magnetic force can do work. However, **a magnetic force never does work**. Consequently, the force that lifts a train or pulls a paper clip to a magnet cannot be a magnetic force. Of course, a magnetic force is involved and, in fact, is often equal to the actual force involved. However, for the reason given in the previous paragraph, it is always an electrical force that lifts a train or wire or pulls a paper clip.

Theory A schematic of the important part of the present experiment, two parallel bars (thick wires), is shown in the next diagram. In section 28-2 of the textbook it is shown that the magnitude of the force, $|\mathbf{F}| = F$, on a length, l, of the upper bar is



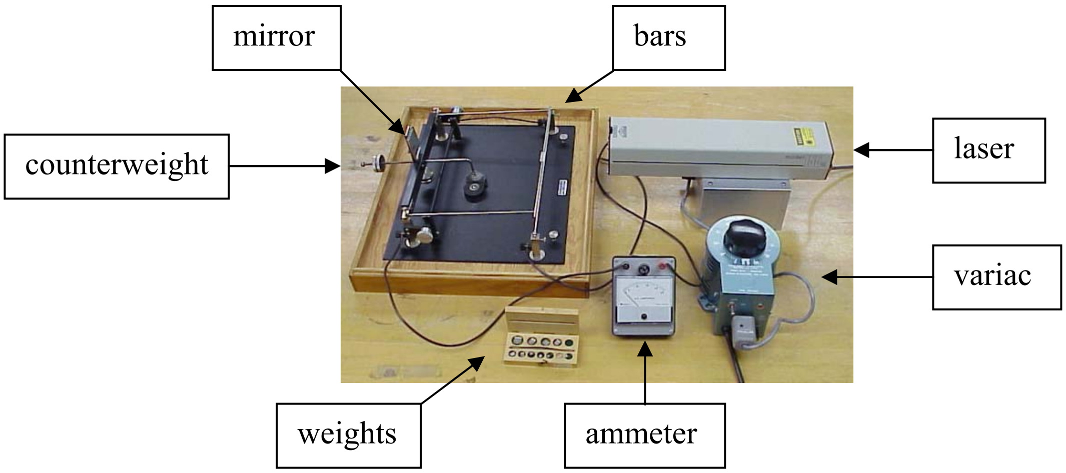
Text eq. [28-2] $$\frac{F}{l} = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{d} \qquad (1)$$

The quantity d is the distance from the center of one bar to the center of the other. Also, in the present experiment, both the upper and lower bars are part of a series circuit. Thus, the magnitudes of the currents are equal i.e. $I_1 = I_2 = I$. Consequently, eq. (1) becomes

$$\frac{F}{l} = \frac{\mu_0}{2\pi}\frac{I^2}{d} \qquad (2)$$

We will make measurements that will enable us to experimentally determine μ_0.

Equipment A picture of the equipment that we will use is shown in the next picture.



Measuring the Force

1. Adjust the bars so that they are parallel to one another and one bar is directly over the other. This may require some adjustment of the lower bar via the screws on the posts supporting the lower bar.

2. Adjust the counterweight so that the bars are in equilibrium a few millimeters apart. Be sure that the bars are in the proper position after adjusting the counterweight. (As stated in step 1, the bars should be parallel and one bar should be directly above the other.)

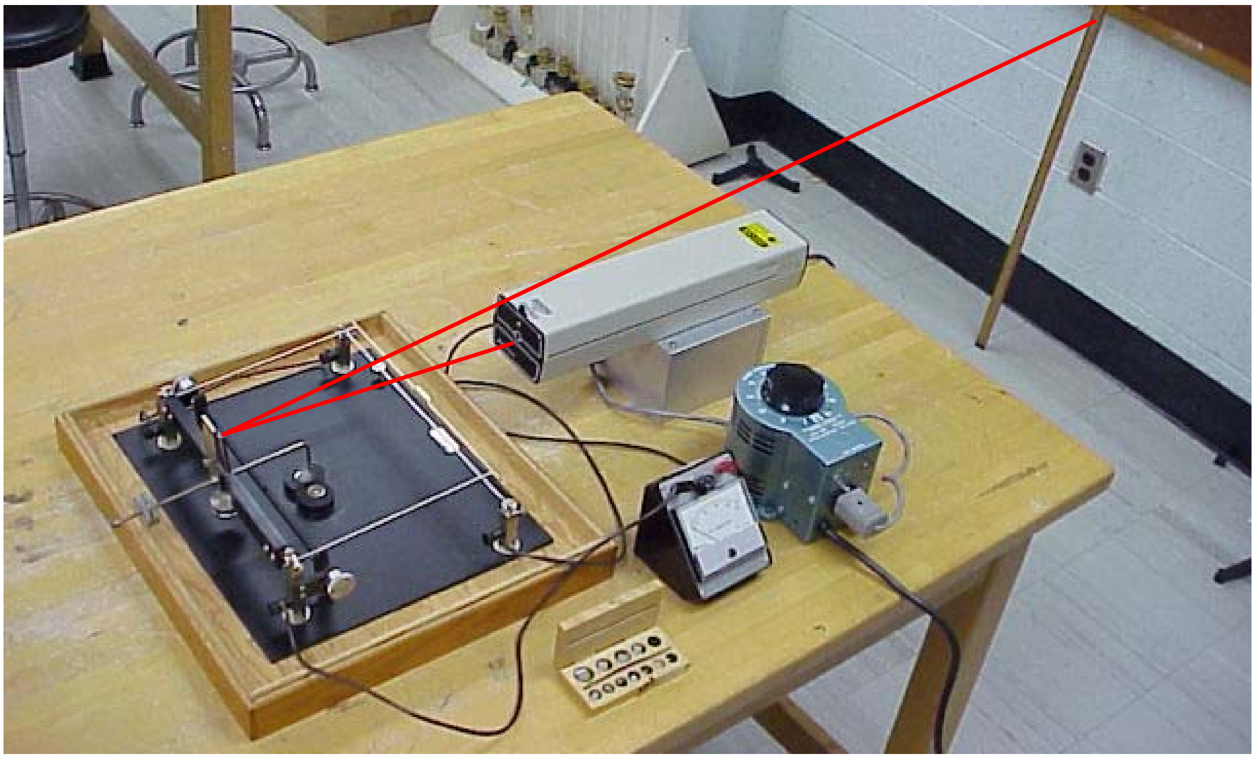
3. Be sure that the upper bar is able to move up and down freely. There is a “damping vane” attached to the movable part of the circuit that might bump into magnets attached to the base. Be sure that it doesn’t. (The “damping vane” and magnets act as an “eddy current brake” to keep the bar from oscillating freely.)

4. The purpose of this step is to test whether the equipment is operating properly. Turn the dial on the variac fully counterclockwise (to zero). Use the switch to turn on the variac. Slowly turn up the variac. Hopefully, current will appear in the circuit and the upper bar will levitate. If not, consult your instructor.

5. Turn the dial on the variac to zero and turn it off. We are ready to use the laser.

Note: Do not let the laser beam shine into your eye i.e. do not look into the laser. It is o.k. to look at the spot where a laser beam strikes a surface so long as the surface is not shiny.

6. Turn on the laser and shine the beam on the mirror so that it reflects and shines on a vertical meter stick (or a piece of paper) a meter or so away (the further away, the better). A picture of the experimental configuration is shown below. (The ammeter in the picture may be different than the one that has been provided.)



7. Be sure that the bars are parallel and are a few millimeters apart. This will be the equilibrium position for the upper bar.

- **Note: The equipment is sensitive and vibrations will move the bars. This will change the equilibrium position and thus cause the experiment to give poor results. Consequently, for the remainder of the experiment, do not touch the table (write on paper on the table, bump the table, etc.).**

8. The position of the (laser) spot on the meter stick (or piece of paper) is a sensitive measure of whether the upper bar is in equilibrium. More importantly, later in the lab, we will use this position in a determination of the distance between the bars. Record the reading on the meter stick as y_2 in the space provided. (If you use a piece of paper, mark the spot on the paper and

label it as y_2.) The spot is large so describe what position within the spot that you are using for y_2.

R1: y_2 = ________ ± ________ m.

The equilibrium position should be checked occasionally throughout the experiment. If it changes, you must discard your data and begin again.

Next, we will add weights to the upper bar and increase the current until the bar returns to equilibrium. When the bar is in equilibrium, the downward (normal) force on the bar due to the weights is balanced by (equal and opposite to) the upward force on the bar due to the electrons moving through it.

9. There should be a pair of tweezers in the box of weights. Use the tweezers to place a 20 mg mass on the upper bar. This should lower the upper bar (and the position of the laser beam on the meter stick or paper).

10. Turn on the variac and turn up the current until the upper bar returns to its equilibrium position as judged by the position of the laser beam on the meter stick.

R2: Record the current in the appropriate space in the third column of the next table.

11. Add masses in about 20 mg increments and repeat the previous step.

M (milligrams)	$F = Mg$ (N)	I (A)	I^2 (A^2)
20.0 ± 0.1			

Data Analysis

1. Plot the force (y-axis) vs. the current (x-axis). The best way to do this is to use **Excel**.

R3: Depending on directions from your instructor, either **Print** the graph or provide your instructor with an electronic copy.

R4: What is the shape of the force vs. current plot? Is it linear? What should it be? Explain.

2. One technique for analyzing the data is to best fit a quadratic equation to the data. In that case, the coefficient of the quadratic term should be $\mu_0 l/2\pi d$. If you do not wish to do this, go to step 3. If you do, carry out the procedure and go to step 4.

3. Another technique for analyzing the data is to plot the force vs. the *square* of the current. In that case you should get a straight line and the slope should be $\mu_0 l/2\pi d$.

4. Record the experimental value in the space provided and carefully describe how you arrived at this result.

R5: $\dfrac{\mu_0 l}{2\pi d} =$ __________ ± __________ N/A^2

R6:

It should be apparent that if we can determine values of d and l, we can calculate an experimental value for μ_0 that can be then compared with the correct value of $\mu_0 = 4\pi \text{x} 10^{-7}$ N/A^2.

Measuring the Separation Between the Wires, etc. Partly because it is small, the most difficult quantity to determine is the distance between the centers of the bars, d. We will do that two ways.

1. Be sure that the variac is off and all masses are removed from the bar.

2. Being careful not to bump the upper bar, use the digital calipers to measure a crude value of d. Record the value in the space provided.

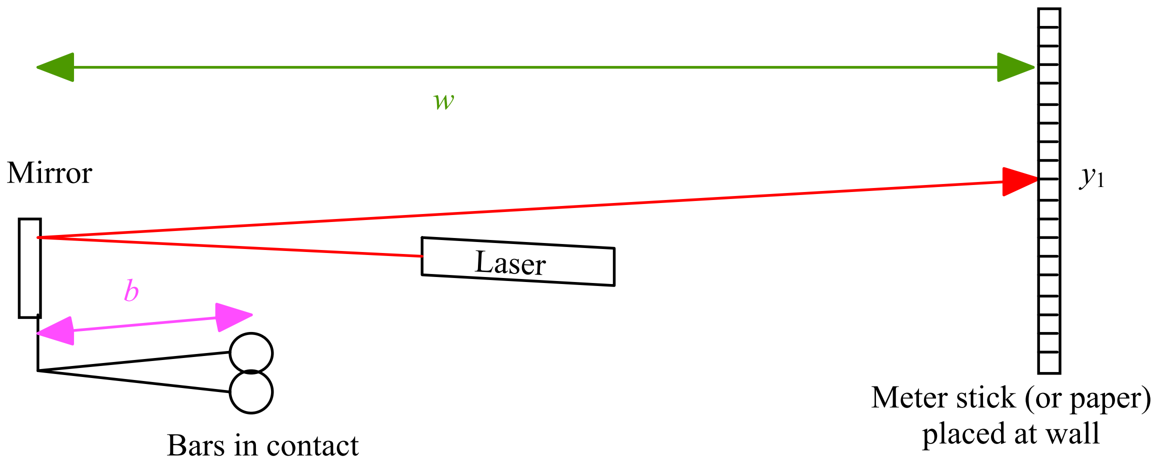
R7: $d =$ ________ ± ________ m.

There is a better way to determine the value of d. We can use the principle of the "optical lever." The basic idea is that if a light beam (in this case our laser beam) reflects off a mirror and the mirror rotates by an angle, θ, the light beam rotates through an angle 2θ. This improves the sensitivity to (angular) rotations. What we will do is to push the wires together then let it return to the equilibrium position. For this process, we will determine the angle swept out by the laser beam (2θ) as the upper wire proceeds from the contact position to the equilibrium position. The (angular) rotation of the laser beam will then be used to calculate the separation *between* the wires, s. If we add the radii of the wires to s, we will get d. Proceed as follows.

3. Place a small mass on the upper bar so that the bars are in contact. A sketch is shown in the

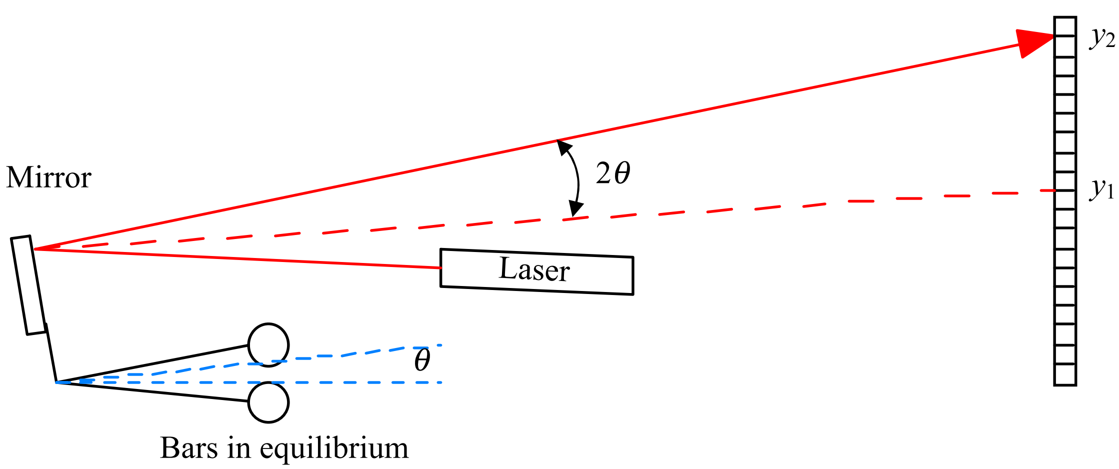
next diagram. Record the position of the spot on the meter stick as y_1. (If you are using a piece of paper, mark the position on the paper and label it y_1.)

R8: y_1 = ________ ± ________ m.



4. Remove the small mass and allow the upper bar to return to the equilibrium position. Re-record the value of y_2 in the space provided. (A sketch is shown in the next diagram.) The value of y_2 should be the same as was recorded earlier in the laboratory.

R9: y_2= ________ ± ________ m.



5. Determine the value of $y_2 - y_1$ and record the value in the space provided.

R10: $y_2 - y_1$ = ________ ± ________ m

6. Measure the distances, w and b, shown in the diagrams. Record the values in the space provided.

R11: w (distance from the mirror to the meter stick) = ________ ± ________ m

R12: b (distance from the top bar to the pivot point of the bars) = ________ ± ________ m

We are now ready to make some calculations. First, remember that s is the *separation* between the bars as shown in the next diagram. Next, we use small angle approximations to write that

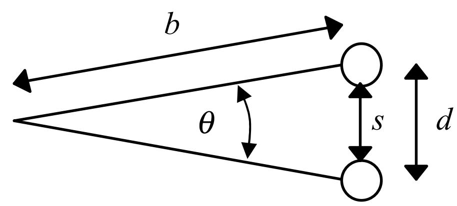
$$s \approx b\theta \qquad (3)$$

and

$$y_2 - y_1 \approx w(2\theta) \qquad (4)$$

Thus,

$$s \approx \frac{(y_2 - y_1)b}{2w} \qquad (5)$$



7. Use eq. (5) to calculate the value of s and record the value in the space provided.

R13: s = ________ ± ________ m

8. Finally, it should be apparent from the last diagram that the distance from the center of one bar to the center of the other, d, is given by

$$d = s + R_1 + R_2 \qquad (6)$$

R_1 and R_2 are the radii of the two bars. Measure R_1 and R_2 and record the values in the space provided.

R14: R_1 = ________ ± ________ m R15: R_2 = ________ ± ________ m

9. Calculate the value of d using eq. (6) and record the value in the space provided.

R16: d = ________ ± ________ m

R17: Compare the two values of d. (If they are significantly different, then you have made a mistake.)

10. Finally, measure the length of the upper bar (parallel to the lower bar) *where there is current*. Record the value in the space provided.

R18: l = __________ ± ___________ m

Data Analysis and Discussion

Use the value of l, the best value of d and the experimental value of $\mu_0 l/2\pi d$ to calculate an experimental value for μ_0 and record it in the space provided.

R19: $\mu_0 =$ __________ ± ___________ T - m/A

R20: Compare the experimental value of μ_0 with the correct value.